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Physica C 403 (2004) 200–202
PHYSICA C
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Temperature dependence of magnetic penetration depth in $B_{1-x}K_xBiO_3$ superconductor

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Received 25 September 2003; received in revised form 25 September 2003; accepted 11 December 2003

Abstract

Temperature behavior of the magnetic penetration depth, $\lambda(T)$, was measured in the Meissner state of $B_{1-x}K_xBiO_3$ ($x = 0.37$) single crystal using tunnel diode oscillator technique. Measurements were carried out down to 0.4 K. At low temperatures, $0.013 \leqslant T/T_c \leqslant 0.4$, $\lambda(T)$ is exponentially flat, which provides a strong evidence for conventional s-wave BCS behavior.

PACS: 4.25.Ha; 74.70.−b
Keywords: Magnetic penetration depth; BKBO; Pairing symmetry

Magnetic penetration depth is an effective tool to study properties of superconductors. At low temperatures, its temperature dependence is directly related to the density of low energy quasiparticles, which in turn can be related to the anisotropy of the superconducting energy gap on the Fermi surface. For investigation of the low lying excitations and thus the anisotropy of the energy gap, the analysis is considerably less ambiguous if data are taken on high quality single crystal and temperatures well below $T_c/3$. In this paper we report penetration depth measurements on $B_{0.63}K_{0.37}BiO_3$ ($T_c \approx 31$ K) down to 0.4 K. The investigation of the superconductivity in $B_{1-x}K_xBiO_3$ (BKBO) system has been one of the major subjects in studies of high T_c superconductivity in oxide materials. The importance of the BKBO system lies in the fact that some of its superconducting properties are consistent with the conventional s-wave isotropic superconductivity, but others resemble high-T_c cuprates. In particular, substantial isotope effect [1,2], strong phonon spectrum from the neutron scattering measurements [3], onset of a superconducting gap with $2\Delta_0/T_c = 3.5 \pm 0.3$ from the tunnelling and optical experiments [4–7] indicate a significant role of electron–phonon interactions in superconductivity of BKBO. However, the low density of states at the Fermi level with T_c as high as 30 K [2] and insulator–superconductor transition by doping [8] are common with high-T_c cuprates. In contrast to high T_c cuprates which have two dimensional CuO_2 planes, BKBO has simple three dimensional cubic perovskite structure.

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0921-4534/$ - see front matter
doi:10.1016/j.physc.2003.12.007

Single crystal of $B_{1-x}K_xBiO_3$ ($x = 0.37$) was prepared by the electro-chemical method reported elsewhere [9]. DC magnetization was measured by using *Quantum Design* MPMS SQUID magnetometer. Zero-field cooled and field cooled temperature scans taken in external field of 10 Oe are shown in Fig. 1. Superconducting transition temperature of the sample is $T_c \approx 31$ K and the curves show regular superconducting screening with the Meissner expulsion of about 20%, which provides an indication of relatively low pinning. Magnetization loops confirm low pinning behavior.

Penetration depth measurements were carried out using a 13 MHz tunnel diode LC resonator [10,11] mounted in a He^3 refrigerator. The sample was placed on the movable sapphire stage with temperature control from 0.35 to 40 K. During the measurements the sample was exposed to the small *ac* field $H_{ac} \simeq 20$ mOe much less than first critical field, $H_{c1} \approx 750$ Oe at 5 K [12]. The relative resonance frequency shift, $\Delta f = f(T) - f(T_{\min})$, is related to the change of the magnetic penetration depth via $\Delta f = -G\Delta\lambda$, where G is a geometrical factor that depends upon the sample shape and volume as well as the coil geometry [11]. Low temperature behavior of magnetic penetration depth is shown in Fig. 2. The frequency shift in Fig. 2 was normalized by the value of total frequency shift, $\Delta f_0 = f(T_c) - f(T_{\min}) \approx 16307$ Hz. The solid line in the figure represents the fit to a low temperature BCS expression for an s-wave material,

$$\Delta\lambda \approx \lambda(0)\sqrt{\frac{\pi\Delta_0}{2T}}\exp\left(-\frac{\Delta_0}{T}\right). \tag{1}$$

Here Δ_0 is the value of the energy gap at zero temperature [13]. The fitting range was chosen up to $0.33T_c$ to ensure the validity of the low temperature expansion. $2\Delta_0/T_c = 3.53$ corresponds to standard weak coupling BCS value. The dash-dotted line shows the low temperature behavior of magnetic penetration depth predicted for a clean d-wave superconductor [14].

$$\Delta\lambda \approx \lambda(0)\left(1 - \frac{\ln 2}{\Delta_0}T\right). \tag{2}$$

The value of $2\Delta_0/T_c$ for d-wave case was again chosen to be 3.53 in accordance with results of tunnelling and optical experiments.

Clearly the isotropic s-wave BCS curve provides best description of the low temperature penetration depth variation indicating the isotropic nature of superconducting gap for BKBO system. Some apparent noise in the data is because in the

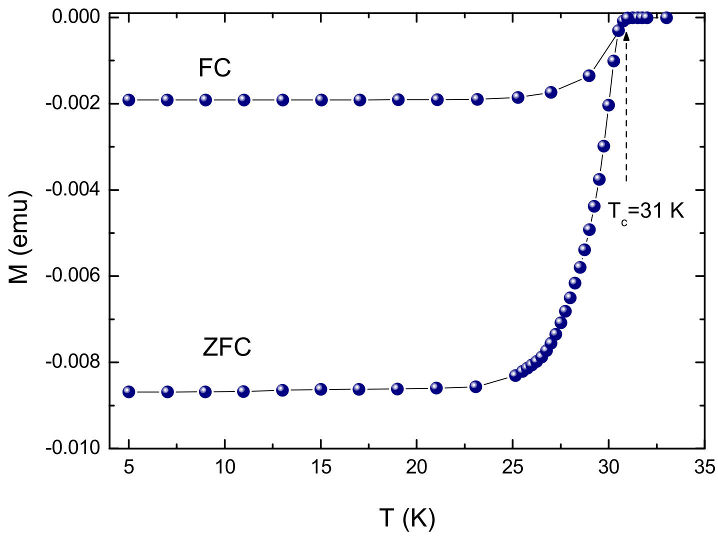

Fig. 1. Temperature dependence of magnetic moment in B–K–Bi–O single crystal in zero-field cooled and field cooled experiment in an external applied field of 10 Oe.

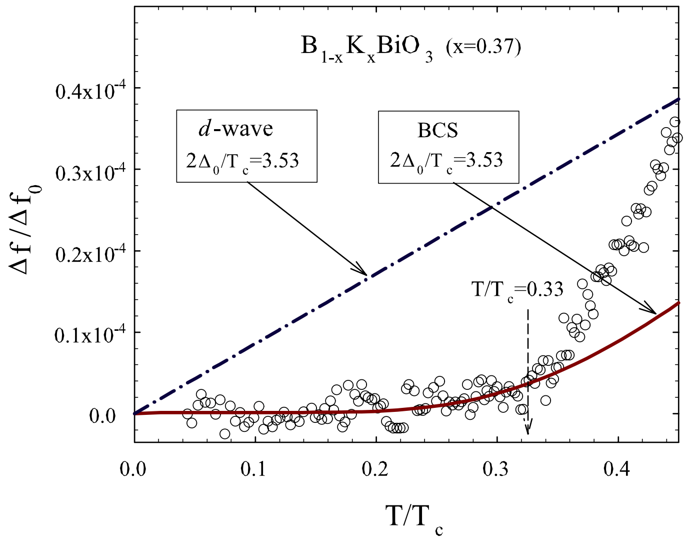

Fig. 2. Low temperature penetration depth variation in $B_{1-x}K_xBiO_3$ ($x = 0.37$) single crystal. The solid line shows the low temperature exponential fit to the weak-coupling BCS expression. Dash-dotted line represents low temperature d-wave behavior. See text for details.

temperature interval of interest, the penetration depth is exponentially flat with no systematic temperature dependence.

Acknowledgements

The authors thank Dr. Hyun-Tak Kim at ETRI for sending us BKBO crystals grown by Dr. W. Schmidbauer and Prof. J. W. Hodby at University of Oxford. Work at the University of South Carolina was supported by NSF/EPSCoR under grant no. EPS-0296165 and USC NanoCenter.

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